Int J Life Cycle Assess (2013) 18:891–908
DOI 10.1007/s11367-012-0533-5

WOOD AND OTHER RENEWABLE RESOURCES

Quantifying the greenhouse benefits of the use of wood products in two popular house designs in Sydney, Australia

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Received: 25 March 2012 / Accepted: 12 November 2012 / Published online: 30 November 2012

Abstract
Purpose As the average wood products usage per unit of floor area in Australia has decreased significantly over time, there is potential for increased greenhouse gas (GHG) mitigation benefits through an increased use of wood products in buildings. This study determined the GHG outcomes of the extraction, manufacture, transport, use in construction, maintenance and disposal of wood products and other building materials for two popular house designs in Sydney, Australia.
Methods The life cycle assessment (LCA) was undertaken using the computer model SimaPro 7.1, with the functional unit being the supply of base building elements for domestic houses in Sydney and its subsequent use over a 50-year period. The key data libraries used were the Australian Life Cycle Inventory library, the ecoinvent library (with data adapted to Australian circumstances where appropriate) and data for timber production from an Australian study for a range of Australian forestry production systems and wood products. Two construction variations were assessed: the original intended construction, and a "timber-maximised" alternative. The indicator assessed was global warming, as the focus was on GHG emissions, and the effect of timber production, use and disposal on the fate of carbon.
Results and discussion The timber maximised design resulted in approximately half the GHG emissions associated with the base designs. The sub-floor had the largest greenhouse impact due to the concrete components, followed by the walls due to the usage of bricks. The use of a "timber maximised" design offset between 23 and 25 % of the total operational energy of the houses. Inclusion of carbon storage in landfill made a very significant difference to GHG outcomes, equivalent to 40–60 % of total house GHG emissions. The most beneficial options for disposal from a GHG perspective were landfill and incineration with energy recovery.
Conclusions The study showed that significant GHG emission savings were achieved by optimising the use of wood products for two common house designs in Sydney. The switch of the sub-floor and floor covering components to a "wood" option accounted for most of the GHG savings. Inclusion of end of life parameters significantly impacted on the outcomes of the study.

Keywords Greenhouse gas emissions (GHG) · Wood · House · Carbon · LCA · Landfill

1 Introduction

The building sector is a major contributor to global greenhouse gas (GHG) emissions—it has been estimated that construction, operation, maintenance and demolition of buildings accounts for 40 % of global GHG emissions (UNEP 2007). In Australia, the residential sector was estimated to account for 13 % of Australia's total GHG emissions in 2005 (CIE 2007). However, this figure does not include emissions from the manufacture of construction materials. Wood products are used for a variety of applications in buildings, and they have the unique characteristic of physically storing carbon (C), both in service and if disposed of in landfills.

Responsible editor: Barbara Nebel

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In Australia, the majority of wood products consumed are disposed of in landfills at the end of their service lives, and it is predicted that disposal of wood waste and end-of-life wood products in landfills in Australia will continue to grow steadily to 2 Mt by 2050 (McLennan Magasanik Associates 2010). Although end-of-life wood products may be recycled at least once, eventually a significant proportion of those recycled products will also end up in landfills. Research conducted in Australia and in the USA strongly suggests that the vast majority of C in wood products if deposited in landfills is stored for the long-term (Ximenes et al. 2008a; Wang et al. 2011).

In addition to physically storing C, the use of wood products in home construction in place of greenhouse-intensive materials, such as steel, aluminium, plastics and concrete, has the potential to reduce the C 'footprint' of house construction further. Wood products require comparatively low fossil-fuel-based energy in their extraction and manufacture, compared to alternative building materials. Research conducted in Australia and New Zealand (e.g. McLennan Magasanik Associates 1991; Buchanan and Levine 1999; May et al. 2011), Europe (e.g. Sathre and O'Connor 2010; Gustavsson, et al. 2006) and in the USA (e.g. Perez-Garcia et al. 2005; Lippke et al. 2011) demonstrates that the life cycle greenhouse impact of wood products is typically significantly lower than that of competing, non-renewable products. From their meta-analysis of 20 European and North-American studies, Sathre and O'Connor (2010) calculate that, on average, for each tonne of C in wood products substituted for non-wood products, a GHG reduction of 2 tonnes of C is achieved.

Despite the significant GHG benefits associated with the use of wood products in the building sector, the average wood product usage per unit of floor area in Australia has decreased from 0.29 to 0.06 m^3/m^2 between 1945 and 2008 (Ximenes et al. 2008b). During this period, there has been an upward trend in the average size of residential dwellings in Australia, from 78 m^2 in 1945 to 250 m^2 in 2008 (Ximenes et al. 2008b). Significant factors in this reduction in wood usage include increases in stud spacing, increased use of brick cladding and a decrease in use of sawn wood in the flooring structure. Up until the mid 1960s, suspended floor systems (with sawn wood bearers and joists) represented approximately 80 % of the sub-floor market—gradually the trend reversed and by the beginning of the 1980s concrete slabs accounted for 80 % of the market, with no significant change since (Ximenes et al. 2008b). This suggests that there is significant scope for an increase in current volumes of wood used in residential construction in Australia. The main current application for wood products in Australia is in the residential market—75 % of the sawn timber is used for residential purposes (BIS-Shrapnel 2008), with 80 % of the sawn pine used for framing applications in houses and approximately 50 % of the sawn hardwood used as sub-flooring and fencing (Ximenes and Gardner 2005). Different products have different service lives, with domestic house framing typically having long average service lives (approximately 50 years for Australia—Ximenes et al. 2008b).

Knowledge of the environmental impacts of alternative building materials in residential buildings is important to inform the development of green building rating schemes. Typically building rating schemes adopt a limited approach in the assessment of the greenhouse implications of the use of construction materials, with a strong focus on the operational energy requirements of the buildings and limited consideration of the greenhouse implications of extraction, transport, manufacture and disposal of different products.

The purpose of this study was to determine the greenhouse outcomes of the extraction, manufacture, transport, use (repairs and maintenance) and disposal of wood products, in comparison with alternative building materials used in the construction of two popular house designs in Sydney, Australia.

2 Methods

2.1 Life cycle assessment software

The life cycle assessment (LCA) was undertaken using SimaPro 7.1 LCA software, and two major data libraries were used:

1- The Australian Life Cycle Inventory (LCI) library, developed by the Centre for Design at RMIT and Life Cycle Strategies Pty Ltd.
2- The ecoinvent library (ecoinvent Centre 2007), with data adapted to Australian circumstances where appropriate.

In addition to these two libraries, the project utilised data for timber production from an Australian CSIRO study for a range of Australian forestry production systems and wood products (Tucker et al. 2009).

2.2 Functional units and assessment options

The overall functional unit for the study was the supply of base building elements for a domestic house (a single storey design and a two-storey design) located in Sydney, New South

Table 1 House designs assessed

	Affinity	Villina
Storeys	1	2
Rooms	9	9
Bedrooms	4	4
Floor area (m^2)	221	296
Site landscape	Flat	Flat

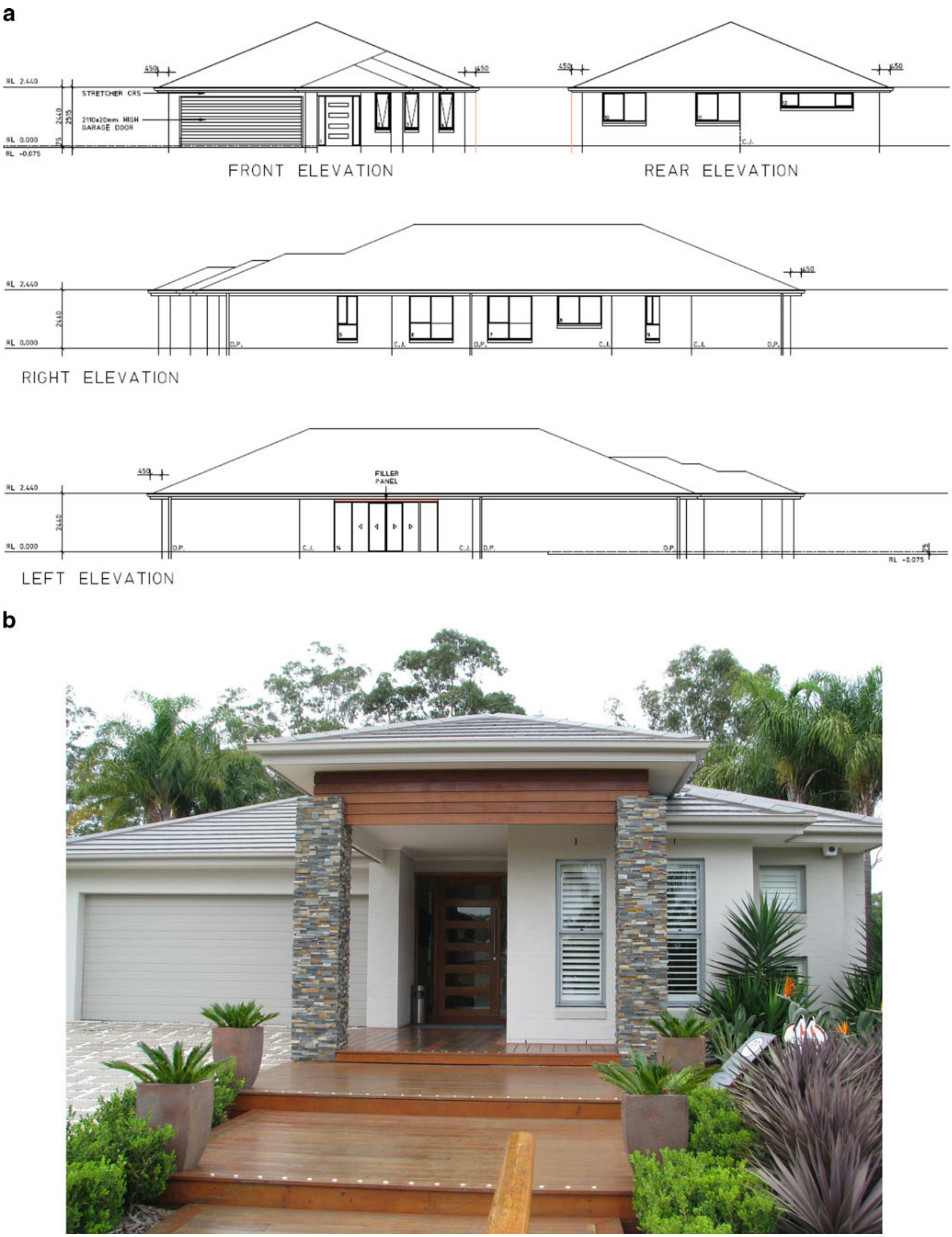


Fig. 1 **a** Layout of an Affinity house. **b** Front view of an Affinity house

Fig. 2 **a** Layout of a Villina house. **b** Front view of a Villina house

Wales (NSW) and its subsequent use over a 50-year period (average service life of houses in Australia), including essential maintenance and replacement of these elements.

2.2.1 Options assessed

The two designs assessed were typical of the house types built by Masterton Homes in Sydney (Table 1, Figs. 1 and 2). Masterton Homes is one of the largest builders of new dwellings in NSW (HIA 2008). Alternative construction materials were identified for specific building elements (Table 2). The combinations of materials in each building element were selected to reflect realistic alternatives on a component level. For each of the two house designs, two construction variations were assessed: the original intended construction and a “timber-maximised” alternative, resulting in four scenarios:

1. “Affinity” single-storey house (original)
2. Affinity single-storey house with timber maximised throughout
3. “Villina” two-storey house (original)
4. Villina two-storey house with timber maximised throughout

For each variation, it was ensured that the engineering integrity of the house was preserved; i.e. the house would have been safely built. In each case the original design and its variation provided the same floor space.

2.3 System boundaries

The phases included in the study are shown in Fig. 3. These comprise:

- Material production (including emissions associated with extraction, transport and processing)
- Transport of materials to site
- Maintenance and repairs
- Disposal of waste produced on site and of end-of-life materials

The following parameters were excluded from the analysis:

- Energy for construction, human labour, energy used in demolition and associated GHG emissions.

  These parameters are often excluded from LCAs of buildings as they are deemed to account for a minor proportion of the overall GHG emissions of buildings (Gustavsson and Joelsson 2010).
- Direct operational energy inputs

  As direct operational energy inputs are highly dependent on the climatic zone, a detailed analysis of the impact of climatic zones on building operational energy requirements of buildings was outside the scope of this study, Therefore energy input during operation phase was excluded from the LCA. A limited supplementary analysis of the potential operational energy requirements of the houses was carried out (see Section 3.7).
- Carbon dioxide (CO_2) emissions from decomposition of organic materials (both above-ground and in landfills)

  CO_2 emissions from decomposition of organic materials were excluded as is common practice in GHG assessments involving organic materials; biogenic CO_2 is deemed neutral as the assumption is that the CO_2 will be sequestered again by growing plants (US EPA 2006) and we assume that the timber is supplied from sustainably managed forests.

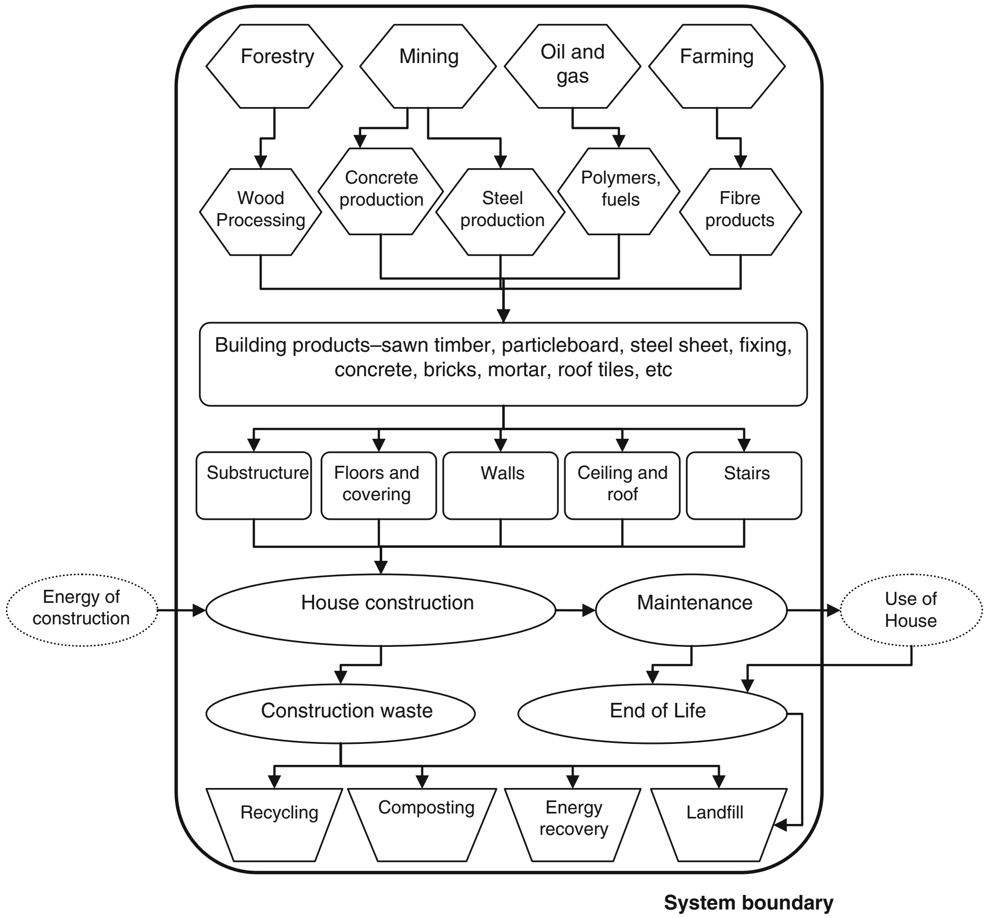
2.4 Indicators

The focus of this study was on GHG emissions, and the effect of timber production, use and disposal on the fate of C. Therefore the indicator assessed was global warming, expressed as GHG emissions in CO_2 equivalents (CO_2-e). Other indicators which may be of particular importance for materials LCA (e.g. biodiversity) were not included in this study—biodiversity assessment still requires a common metric that can be universally applied in LCAs (e.g. Penman et al. 2010).

Table 2 House as designed and alternative construction materials assessed for individual building elements

Component	Materials		
	Original design	Alternatives	
Sub-floor	Concrete slab	Timber bearers and joists	Steel
Flooring living area	Carpet/carpet and particleboard (on 1st floor)	Hardwood tongue and groove (T&G)	
Flooring kitchen	Ceramic tiles	Linoleum	
Wall structure	Brick veneer; timber frame	Brick veneer; steel frame	Double brick
Windows	Aluminium	Timber	MDF
Roof frame	Timber	Steel	
Roof material	Concrete tiles	Corrugated metal (Colorbond®)	
Upper storey (flooring)	Carpet/particleboard	Hardwood	Ceramic tiles

Fig. 3 System boundary for the LCA study



2.5 Inventory

2.5.1 Wood products

Assumptions for wastage and end of life options for wood products are shown in Table 3. The gate to gate inventory data (for sawn and engineered wood products such as plywood, particleboard and MDF) were linked to electricity and transport data from the RMIT Centre for Design LCA database, with missing inventory items, such as resins, being taken from the ecoinvent database.

In this study, it was assumed that the forest producing the timber is in steady state with no net increase or decrease in C stored in the forest over time. The study also assumed that timber production will increase, through expansion of plantation area, or through increase in the sustainable yield from existing forests, as demand for timber increases.

Table 3 Waste and end of life assumptions for wood products

Building component	Material	Waste factor[a]	End of life assumption	Comment
Bearers and joists	Sawn hardwood	1.1	Landfill/recycling	Timber is assumed to be untreated; 20 % of hardwood is assumed to be recycled
Wall and roof framing	Softwood framing	1.1	Landfill/recycling	10 % of softwood is assumed to be recycled
Particleboard flooring	Particleboard	–	Landfill	None of the particleboard is assumed to be recycled
Bracing ply	Plywood	1.1	Landfill	None of the plywood is assumed to be recycled
Formwork production	Plywood	1.05	Landfill	5 % wastage assumed in original production of formwork
Formwork use	Plywood	1.01	Landfill	1 % of formwork used is assumed to need replacement with the remainder reused

[a] The waste factor refers to the wastage during construction of the house

Table 4 Key parameters used for landfill models—per kilograms of timber sent to landfill

Parameter	Value
Degradable organic carbon (DOC)[a]; dry mass basis (%)	49
Proportion of DOC which degrades—USEPA (%)	24
Proportion of DOC which degrades—DCC (%)	50
Proportion of DOC which degrades—Ximenes (%)	10
Methane portion of landfill gas (%)	50
Methane recovered (%)	55
Methane recovered for power generation (%)	75
Efficiency of power generation (%)	35
Oxidation factor (%)	10
Carbon stored (kg)	0.245
Final CH_4 emissions (kg)	0.058

[a] Listed as 0.43 but this is for air-dried timber, so after accounting for 12 % moisture it is taken as 49 % for timber on a dry basis

2.5.2 Carbon in wood products in landfills

End-of-life wood waste and waste from wood production combined account for 11.2 % of the commercial and industrial (C&I) landfill waste, 1.1 % of the municipal solid waste (MSW) landfill waste and 6 % of the construction and demolition (C&D) landfill waste in Australia (Department of Climate Change and Energy Efficiency 2011). Carbon in wood products in landfills is originally absorbed from the atmosphere by the growing tree—after harvest it remains stored in the wood products during their use, before being sent to landfill, where a portion of the C may be lost due to decay (releasing approximately equal parts of CO_2 and methane (CH_4)).

At landfills with CH_4 capture infrastructure, typically up to 75 % of the CH_4 generated may be captured and either flared or used to generate electricity (Hyder Consulting 2010). Research has shown that the majority of the C in wood products deposited in landfill remains stored for the long-term (Ximenes et al. 2008a; Wang et al. 2011). The factor used by the United States Environmental Protection Agency (USEPA) (2006) for decay of wood in landfills was used as a default in this study, as it was deemed the most realistic of the decay factors currently used for greenhouse reporting purposes. A sensitivity analysis was carried out using a weighted factor suggested for Australian landfills (Ximenes et al. 2008a), as well as the factor used by the Australian Government for the purposes of national GHG estimations (Department of Climate Change 2008). It should be noted that since the study was concluded the Australian Government has adopted the US EPA factor for decomposition of wood in landfills (Department of Climate Change and Energy Efficiency 2010).

The assumptions for the three landfill scenarios are shown in Table 4. The only factor assumed to vary in Table 4 was the extent to which the degradable organic fraction of the timber (the C content of kiln-dried wood is typically 44 %) actually degrades.

Decomposition of wood products in C&D landfills was assumed to be insignificant in this study, as the near absence of moisture and the absence of highly degradable waste (e.g. food waste) in C&D landfills significantly limits the onset of anaerobic decay.

Recycling, mulching and energy recovery through combustion were modelled as alternative end of life scenarios. Softwood timber recycling was based on inventory data from a Victorian study where timber is recycled into low-grade wood products such as pallets or packing crates (Carre et al. 2009). Hardwood timber recycling was based on inventory data obtained from a recycled furniture manufacturer in Sydney who produces furniture from old untreated hardwood fencing. Emissions due to fuel requirements of machinery used for transport and production of mulch were sourced from data contained in ROU (2006). Decomposition of mulch was assumed to occur rapidly, with no long-term carbon storage, and as mentioned above, the resulting CO_2 emissions were deemed neutral due to their biogenic nature. Incineration of timber waste assumed standard combustion emission factors from National Pollutant Inventory workbooks for wood waste (Department of Sustainability, Environment, Water, Population and Communities 2008) and typical energy content and electricity generation for wood (Table 5).

In all of the options above, the net greenhouse benefits either due to the avoidance of production of materials from virgin feedstock (e.g. furniture from virgin hardwood

Table 5 Key parameters for wood combustion for energy generation

Parameters	Values
Energy content of wood waste (MJ/kg)	15
Efficiency of power generation for wood waste (%)	30
Freight distance for wood supply (km)	30
Electricity offset	NSW electricity

Table 6 Avoided products or process assumed for each wood waste utilisation option

Wood waste utilisation option	Avoided product/process
Landfill (municipal solid waste—MSW); generation of electricity from CH_4 recovered	Electricity production from black coal (100 %)
Landfill (construction and demolition—C&D)	None
Recycling	Use of forest resource (plantation timber for softwoods and native forests for hardwoods)
Incineration of timber (with energy recovery)	Electricity from black coal (85 %) and natural gas (15 %)[a]
Mulching	None

[a] Based on the gross energy consumption in NSW

resources or from recycled timber), or due to the generation of energy (electricity produced from CH_4 from landfills displacing the use of electricity generated from black coal in NSW) were modelled (Table 6).

2.5.3 Concrete products

Data for concrete and cement were sourced from the Australian Cement Industry Federation's website and from their GHG reporting tables (Table 7).

2.5.4 Brick products

Data for brick were sourced from the ecoinvent database and adjusted to Australian energy systems and materials (see Table 7).

2.5.5 Steel products

Steel data (see Table 7) were based on data releases from the Australian Steel Institute which had been integrated into existing steel inventories in the Australian LCI database in SimaPro, which was originally based on Dimova (1998a).

2.5.6 Operational energy data

While data on operational energy are not included in this LCA, in the interpretation of results the relative greenhouse impact of the extraction, manufacture, transport, use and disposal of materials is compared to that associated with the operational energy requirements of the houses. These data were taken from AccuRate energy modelling software (CSIRO 2011) in the Sydney climate zone using a typical 3–4-star-rated home (all design options analysed achieved the

Table 7 Concrete, brick and steel products data

Material	Data source	End of life assumption	Comment
Cement	(Cement Industry Federation 2005)	NA	100 km assumed for transport of cement to concrete batching plant
Concrete mix 20MPA	http://www.concrete.net.au/faq.php	80 % recycled remainder to landfill	Includes blast furnace slag (12.5 %) and fly ash (25 %) transport distance is 40 km
Concrete mix 25MPA	http://www.concrete.net.au/faq.php	80 % recycled remainder to landfill	Includes blast furnace slag (12.5 %) and fly ash (25 %) Transport distance is 40 km
Gravel	From Australian Inventory Database (Dimova 1998b)	NA	200 km assumed for transport
Sand	From Australian Inventory Database (Dimova 1998b)	NA	200 km assumed for transport
Bricks, clay	Ecoinvent data base (ecoinvent Centre 2007)	25 % recycling rate for bricks being reused as brick	Brick inventory has been adjusted to Australian energy systems and materials
Structural steel	Australian Steel Institute (Strezov and Herbertson 2006)	85 % recycling rate	10 % recycled content
Steel sheet	Australian Steel Institute (Strezov and Herbertson 2006)	75 % recycling rate	5 % recycled content
Steel reinforcing	Australian Steel Institute (Strezov and Herbertson 2006)	80 % recycling rate	100 % recycled content

same rating). The data were adjusted based on the spatial area of the home modelled in AccuRate to reflect the two houses included here.

3 Results and discussion

The greenhouse implications of the use of various building materials for each of the main components of the house are described below.

3.1 Sub-floor

Three alternative sub-floor structures were assessed: (1) a concrete slab on the ground, (2) a suspended concrete slab and (3) a suspended timber floor on top of a concrete strip footing. The sub-floor in the upper storey of the Villina house was modelled separately.

The "suspended slab" option resulted in the highest greenhouse emissions for both house designs, primarily due to the increased use of concrete (Fig. 4). The use of concrete accounted for the majority of the greenhouse emissions in all three floors, ranging from 72 % for the timber sub-floor option to 90 % of the greenhouse emissions associated with the concrete slab option for the Affinity design. The greenhouse impact of concrete was derived largely from cement production and the steel used in reinforcing concrete (Fig. 5). The timber sub-floor option resulted in reductions in GHG emissions ranging from 31 to 44 % for the Affinity house and 38 to 56 % for the Villina house, depending on the concrete slab system. In a study involving a standard single-storey house in Australia (Carre 2011), similar differences in GHG emissions were found between a concrete slab and a timber elevated floor (not including emissions due to operation and maintenance of the house). The net C storage of wood in landfills was significant for the timber sub-floor option in both designs (see Fig. 4).

Ximenes et al. (2008b) have estimated the GHG savings that would be achieved if there was a significant shift back from concrete slab to timber suspended floor systems in the construction of new dwellings in Australia. Such a shift would result in GHG savings of approximately 600,000 t CO_2-e/year (based on the construction of 150,000 new dwellings per year and assuming 60 % of dwellings that would have been built on concrete slabs were built on timber bearers and joists instead) (Ximenes et al. 2008b).

3.2 Floor coverings

Four floor coverings were modelled in the following combinations: (1) timber (hardwood) and ceramic tiles; (2) carpet (nylon) and ceramic tiles; (3) timber (hardwood) and linoleum; and (4) carpet (nylon) and linoleum. Carpet and polished floors were used in living areas, whereas tiles were used in wet areas (bathroom and toilet), with linoleum an alternative option in the kitchen. Maintenance is an important parameter for floor coverings—in this study the hardwood floor was assumed to be recoated every 10 years, carpets and linoleum were assumed to be replaced every 15 years and tiles every 25 years.

Carpet had the highest greenhouse impact of all floor coverings, while timber hardwood flooring resulted in net GHG savings (Fig. 6). The greenhouse impact for floor covering combinations involving linoleum were very similar to those for floor covering combinations with tiles for

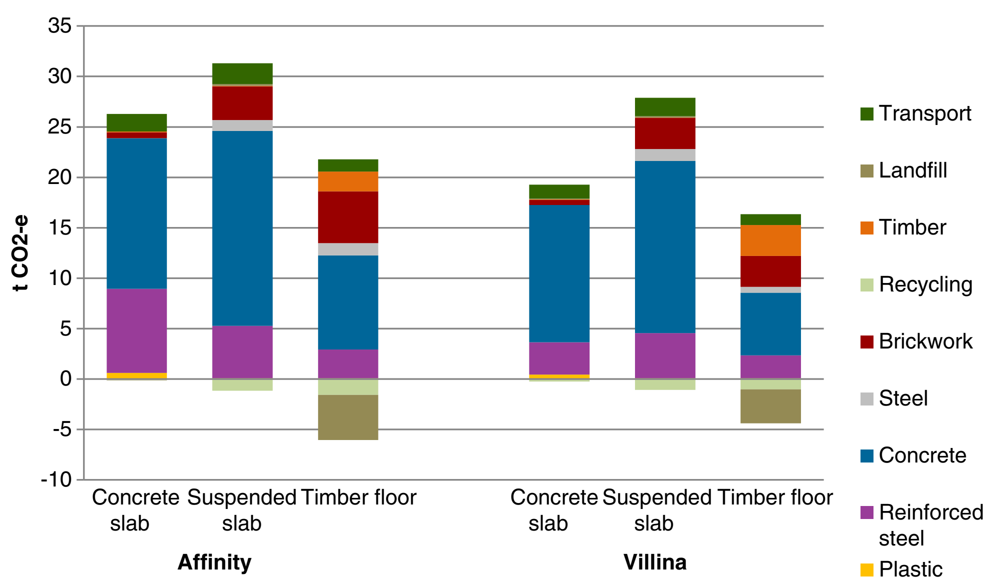


Fig. 4 Greenhouse gas emissions for substructure options

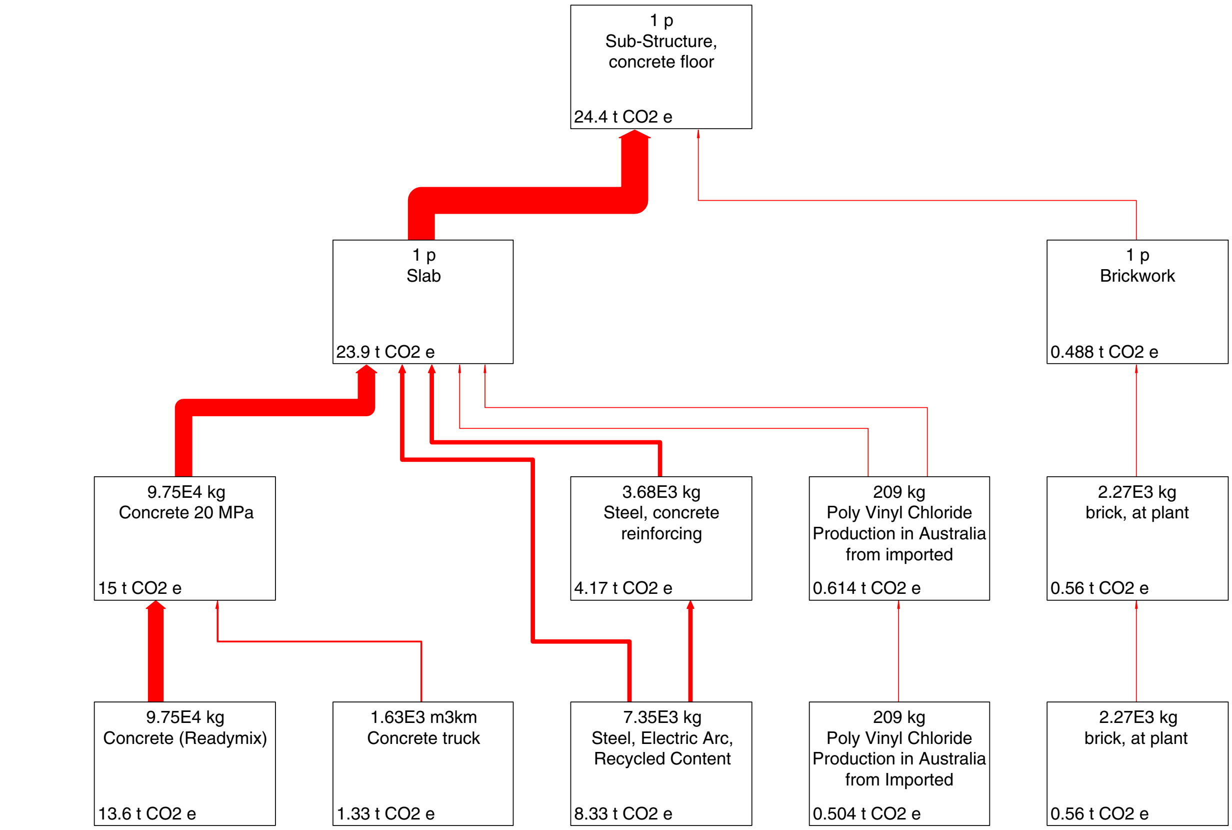


Fig. 5 Process network showing GHG emissions for sub-structure using concrete slab on ground (Affinity)

both house options (results not presented).The use of carpet resulted in emissions of 17.6 t of CO_2-e (Affinity) and 22.4 t of CO_2-e (Villina) per house built. Carpet is made from natural gas and petroleum products—the large fossil fuel intensity of carpet inputs and production makes the emissions of carpet manufacturing extremely high (US EPA 2011). Petersen and Solberg (2004) found that use of nylon carpet resulted in the second highest GHG emission outcome (wool carpet was the highest) compared to alternatives which included solid oak flooring, with the magnitude of the emissions varying substantially according to the scenario modelled.

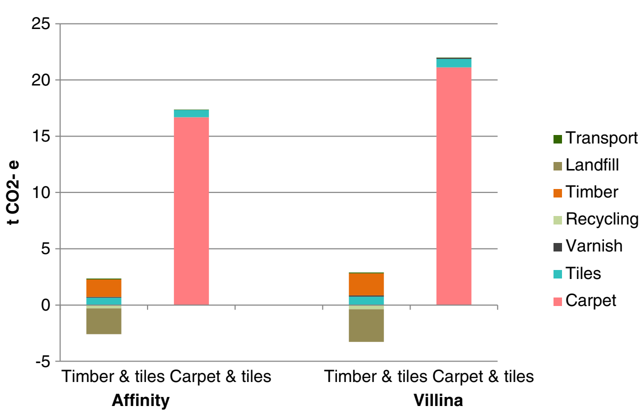


Fig. 6 Greenhouse gas emissions for floor covering options broken down by component

It is important to note that the choice of floor covering may have an impact on the thermal behaviour of buildings, which in turn may alter the magnitude of the GHG differences between the different floor options over the life of the buildings. However, this is unlikely to significantly change the overall trend between floor options modelled given the very large differences in GHG emissions due to the extraction, transport, manufacture and disposal of materials.

3.3 Walls

Three wall types were assessed: (1) a double brick wall, (2) a timber frame brick veneer wall and (3) a steel frame brick veneer wall.

The brickwork dominated the GHG impacts of all wall systems, with the highest impact for the double-brick option (Fig. 7)—the net GHG impacts of the brickwork for both house designs was greater than that of all other elements combined. There were also significant benefits from recycling brickwork at end-of-life, assuming 25 % of used bricks are recovered for reuse (see Fig. 7).

The timber brick veneer option resulted in a reduction of 22 % in GHG emissions compared to the steel brick veneer

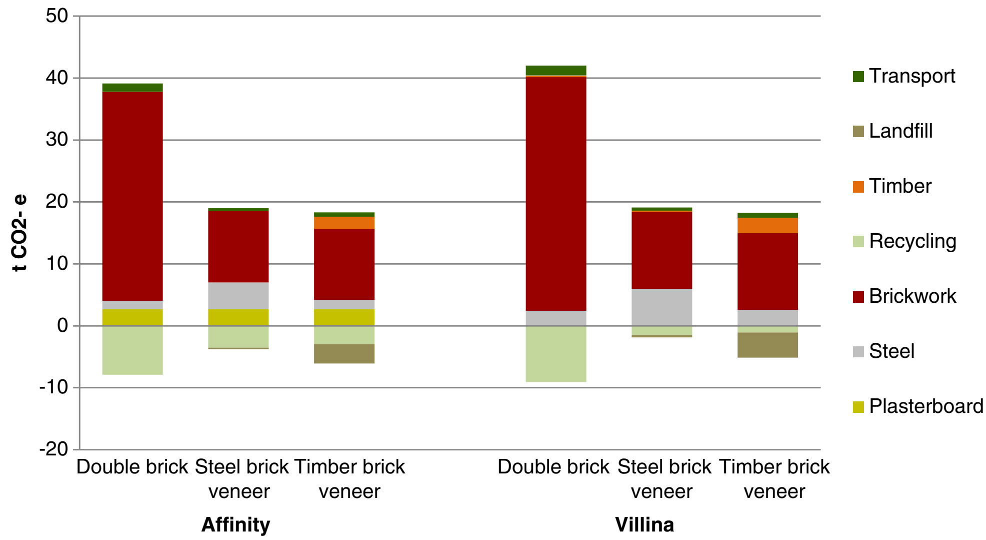


Fig. 7 Greenhouse gas emissions for wall options

option. The differences were primarily due to the higher GHG emissions associated with the manufacture of the steel compared to the timber option, and also due to the C storage of wood in landfills (see Fig. 7). In a study involving a standard single-storey house in Australia (Carre 2011), similar differences in GHG emissions were found between a timber frame brick veneer wall and a steel frame brick veneer wall (not including emissions due to operation and maintenance of the house). In a US study (Upton et al. 2006), it was found that for a residential double-storey dwelling built in Minneapolis (192 m^2), a wood-based wall system resulted in a reduction of approximately 20 % in net emissions compared to a steel-based wall system. The study did not include GHG emissions associated with operational or maintenance activities.

3.4 Roof

Four roof types were assessed: (1) a steel-framed roof with corrugated metal sheeting, (2) a steel-framed roof with clay roofing tiles, (3) a timber-framed roof with corrugated metal sheeting and (4) a timber-framed roof with clay roofing tiles. The tiled roof–steel frame roof type resulted in the highest GHG emissions for all roof types assessed (Fig. 8). Roof tiles had the largest impact in the options in which they were used (see Fig. 8). The timber frame option for the roof resulted in net GHG emission reductions ranging from 51 to 66 % compared to steel frames for the equivalent roofing material. As for the wall options, this difference was due primarily to the higher GHG emissions associated with the manufacture of the steel compared to the timber option, and also due to the C storage of wood in landfills.

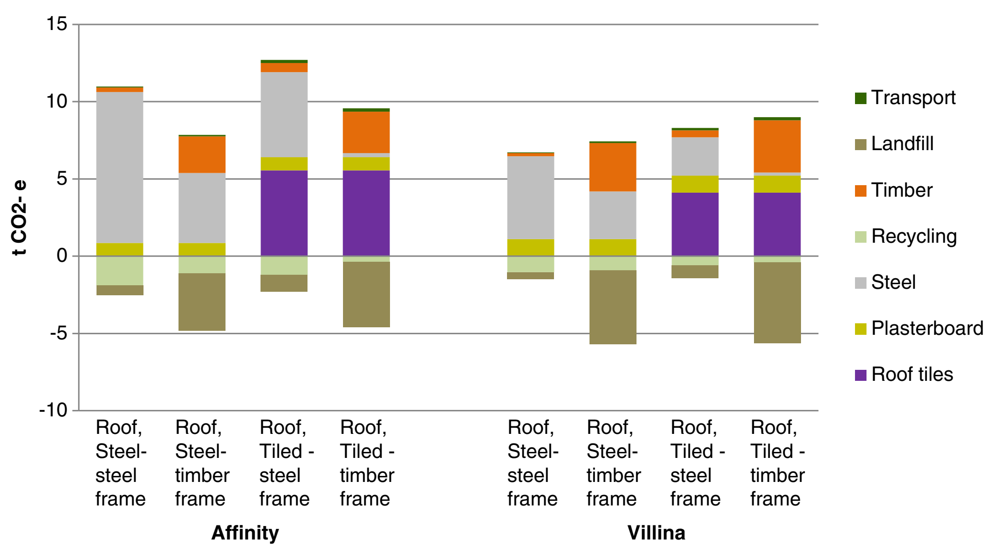


Fig. 8 Greenhouse gas emissions for roof options

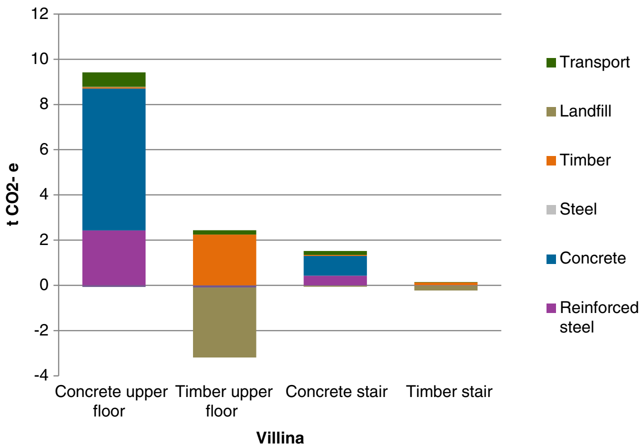


Fig. 9 Greenhouse gas emissions for second storey floor and stairs (Villina)

3.5 Second storey floor and stairs

A concrete and a timber second storey floor and stair were modelled (Fig. 9). The net greenhouse impacts of the timber stair and floor were negative, representing a net reduction in GHG emissions. The greenhouse impact of concrete was substantially higher due to the greater mass and higher emissions associated with the manufacture of concrete. The combined "concrete upper floor and stair" system resulted in 11.6 t CO_2-e per house built.

3.6 Windows

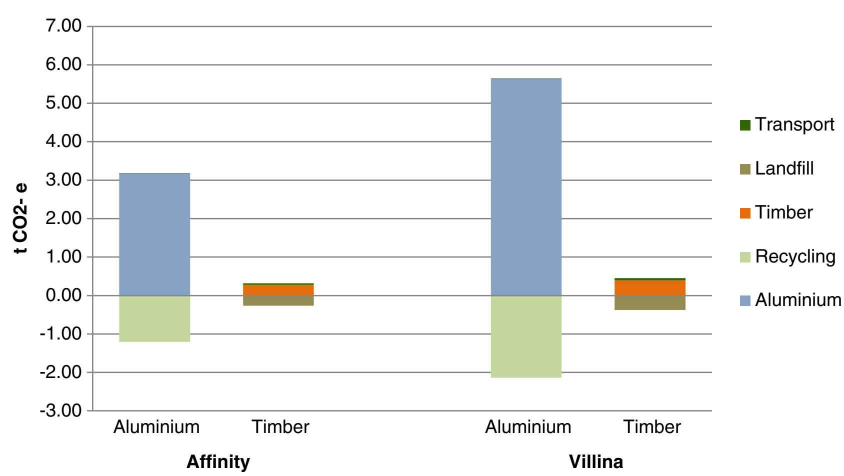
The total material input to windows excluding the glass which was common to both was modelled (Fig. 10). Aluminium windows resulted in the highest GHG emissions due to the high greenhouse intensity of their manufacture. The recovery of aluminium for recycling (assumed here to be 50 %) was significant in ameliorating the greenhouse impacts of aluminium windows. Any recycled aluminium in the feedstock was treated as virgin material, as the credit for using recycled material was allocated to the product system from which the scrap had been derived. Timber windows were produced from Malaysian meranti and disposed of to landfills at the end of their lives.

3.7 House structure as a whole

The GHG emission profile of the houses by major structural components and by materials is shown in Figs. 11 and 12. The timber maximised design resulted in approximately half the emissions associated with the base designs (see Fig. 11). As the internal framing (wall and roof) of the "house as designed" was already primarily made of wood, they were not changed in the "timber maximised design". The key GHG emissions reductions in the "timber maximised design" compared to the "house as designed" house were caused by increasing the usage of wood in the sub-floor, floor covering and windows (see Fig. 11), as the materials displaced (concrete, carpet and aluminium) have a high greenhouse footprint.

The sub-floor had the largest greenhouse impact due to the concrete components, followed by the walls due to the usage of bricks. The floor covering was the next largest contributor to GHG emissions, which in the "house as designed" option was due to the use of carpet in the living areas. In a similar study conducted in Canada for a double-storey brick veneer house (Salazar and Meil 2009), similar GHG emission reductions were reported for a "timber maximised design" compared to a typical house design (including emissions from wood in landfills). The primary difference in GHG emissions due to use of material between the two designs used in that study was in the use of brick cladding in the typical house and cedar siding for the wood intensive design (sub-flooring and floor covering options were not assessed). Salazar and Meil (2009) also assigned increased credits due to forest regrowth to the "timber maximised design" in their study, as a result of the beneficial long-term effect of sustainable forest

Fig. 10 Greenhouse gas emissions for window options



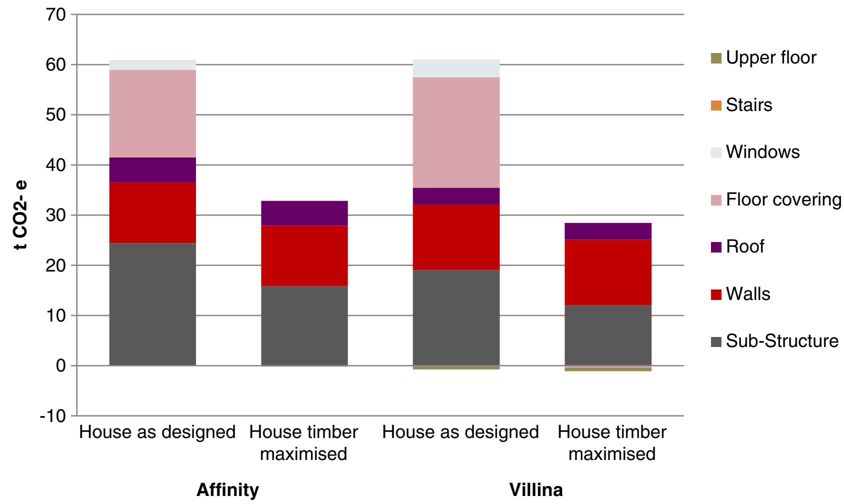


Fig. 11 Greenhouse gas emissions for house as originally designed and with timber usage maximised by component

management on C storage levels in the forest/wood product system. Without that component, the GHG emission savings of the "wood maximised design" would have been reduced to 18 %. Although the GHG emission reductions due to increased use of wood in the "timber maximised design" were very significant, there are a number of possible factors that could increase the GHG benefits and use of wood even further, including:

- Improvement in efficiency of forest operations and in sawmill recoveries
- Technical improvements to increase service life of materials and to increase recycling potential of products at time of demolition
- Innovations in types of products and their potential uses (e.g. cross-laminated timber usage in multi-storey buildings)

A preliminary analysis of the potential operational energy of the houses (service life of 50 years) was carried out in order to gain an insight into the relative greenhouse impact of the extraction, manufacture, transport, use and disposal of materials compared to the operational energy requirements of the buildings (Fig. 13). Under this scenario, operational energy for heating and cooling generated between two and three times the greenhouse emissions compared with the extraction, manufacture, transport, use and disposal of materials (see Fig. 13). In a recent study for a standard Australian home built in Sydney (Carre 2011), the GHG emissions due to operational energy requirements of the house were approximately equal to those from materials and construction, maintenance and end of life. However, in that study the houses were assumed to comply with a five-star rating performance, which would incur less operational energy emissions than the houses modelled here.

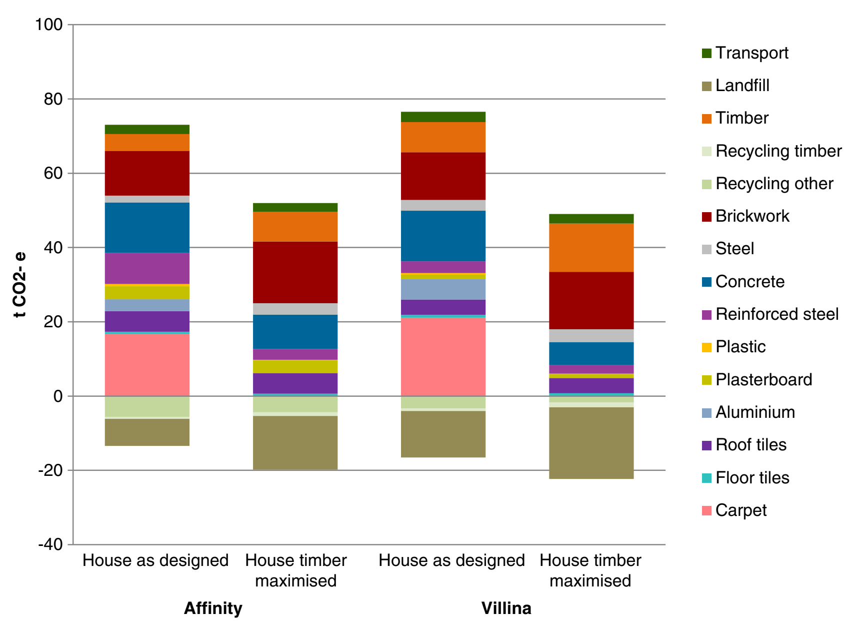


Fig. 12 Greenhouse gas emissions for house as originally designed with timber usage maximised by material and life cycle component

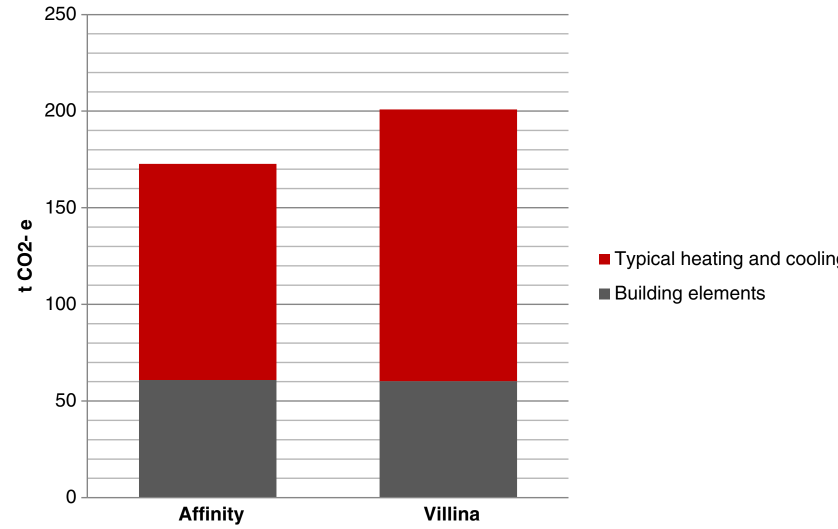


Fig. 13 Greenhouse gas emissions for construction of the house as designed compared to heating and cooling loads in Sydney

The decrease in GHG emissions associated with the use of a "timber maximised" design as outlined above would offset between 23 and 25 % of the total operational energy of the Villina and Affinity houses, respectively (see Figs. 12 and 13). This assumed that the choice of wood in the sub-floor, floor covering and windows did not incur any additional operational energy requirements for the houses. As data on the operational performance of specific building components are difficult to apply due to their high dependence on choice of climatic zone, other studies have adjusted building designs to achieve common energy performance (e.g. Carre 2011; Perez-Garcia et al. 2005), Gustavsson and Joelsson (2010) concluded that for a wood-maximised house in Sweden, the reduction in operational energy achieved when adjusting the building

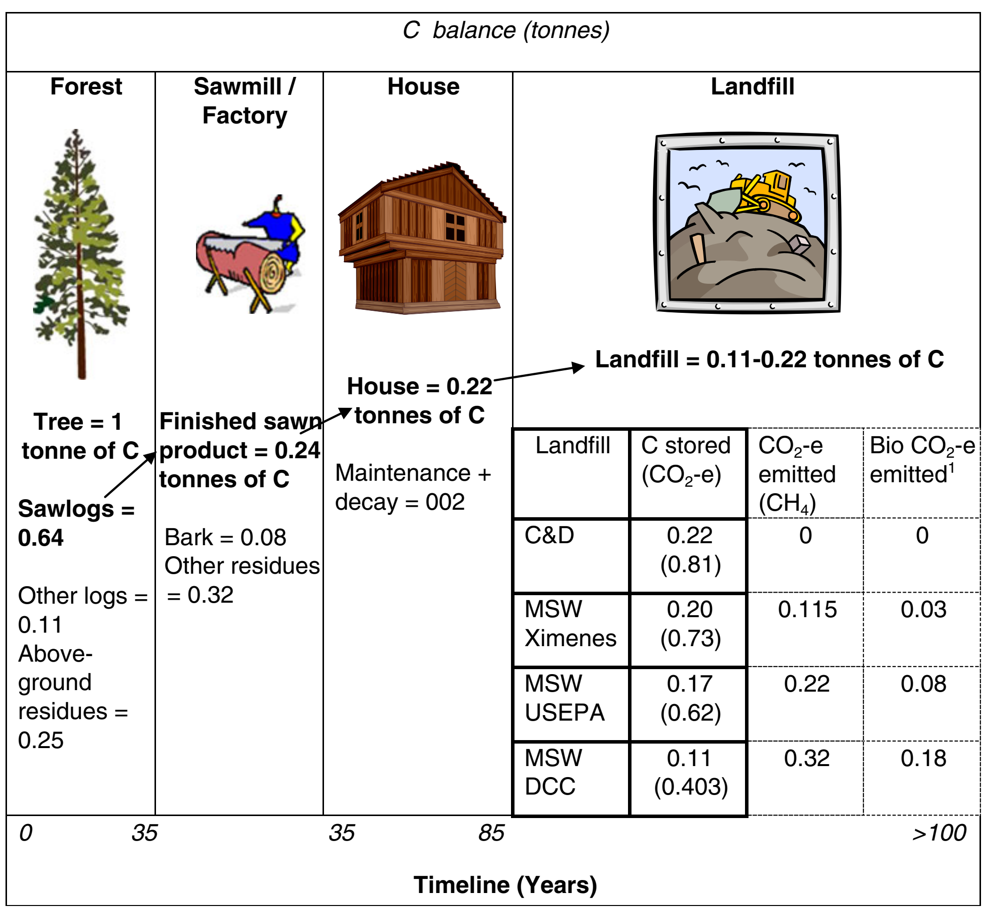


Fig. 14 Long-term carbon storage—example of house wall frames made from Radiata pine (*Pinus radiata*) plantations, using landfill as the disposal option

design by adding insulation and installing energy-efficient windows was ten times that of the increase in production energy that was required to produce these materials.

3.8 End of life variations

The impact of the different landfill pathways on the carbon balance of the forest/wood product/disposal system is illustrated in Fig. 14. The carbon is initially stored in the forests (in this example for 35 years as that is the typical age of harvest for radiata pine managed for sawlogs in New South Wales, Australia). The proportion of the carbon in the trees that is stored in sawn wood products is stored in the houses (in this example wall frames) for the duration of their service life (apart from minor losses due to decay and maintenance). Finally, the majority of the wood frames are typically disposed of in C&D landfills (see Fig. 14). The C storage implications of disposal in MSW landfills (mostly relevant for offcuts and home wooden articles such as broken furniture) are also demonstrated for a range of decomposition factors (see Fig. 14).

The inclusion of long-term C storage in wood products in landfills (base scenario) in the LCA modelling had a significant impact on the greenhouse footprint of the houses, equivalent to between 14.4 and 16 t CO_2-e for the houses assessed or 40–60 % of total house GHG emissions (Table 8).

Given the significant impact of the end of life option on the overall greenhouse impact of the house designs assessed, a number of scenarios were considered in addition to those modelled above. The landfill options included a range of decomposition factors for landfills (MSW and C&D landfills, Fig. 15). The gas generation profile showed a balance between C stored in the landfill and GHG emissions as CH_4, which is either used for power generation, flared or emitted into the atmosphere. The higher degradation rates led to higher CH_4 emissions and less C storage in landfill. The choice of decomposition factors changed wood in landfills from being a C store (options B, C and D) to net emitters of GHG emissions (option A). Disposal in C&D landfills lead to the highest net C storage of all landfill options (−1.78 t $CO2\text{-}_e$), as there are reduced opportunities for decomposition of wood in those landfills due to the absence of food waste.

Salazar and Meil (2009) adopted the same key landfill parameters used in this study, with one key difference—the CO_2 emissions from decay in landfills were included in the assessment, as the study also included credits for forest regrowth, and thus avoided double-counting. This explains why the “landfill” option in Salazar and Meil’s study resulted in net GHG emissions.

The GHG benefits of recycling of wood products were limited due to the already low greenhouse footprint of wood products production (options E and F). The wood type (hardwood or softwood) did not have an impact on the overall greenhouse footprint of recycling (see Fig. 15). Mulching of the wood led to an almost neutral greenhouse outcome, as it requires minimal processing and the C in the wood is released back into the atmosphere within a short period of time.

Incineration with energy recovery had significant greenhouse benefits (option H). The only two impacts were the small CH_4 and nitrous oxide emissions from combustion with the benefits coming from electricity offsets, which in the case of NSW are significant (black coal). Incineration without energy recovery had minimal greenhouse impacts (option I), as biogenic CO_2 emissions are deemed neutral.

The impact of changing the wood waste disposal option on the overall GHG emissions of the components in the timber maximised option (mean of the results for the two designs) is shown in Table 9. The results for the “landfill DCC” option, “mulching” and “incineration without energy recovery” are not shown because they did not lead to significant GHG emissions or C storage. A change of decomposition factors for wood in landfills led to increased greenhouse savings ranging from 16.7 to 25.8 t CO_2-e (average of the timber maximised designs)—this nearly completely offset the GHG emissions associated with the timber maximised designs (see Fig. 11). A switch to incineration with energy recovery also led to significant additional greenhouse savings (see Table 9).

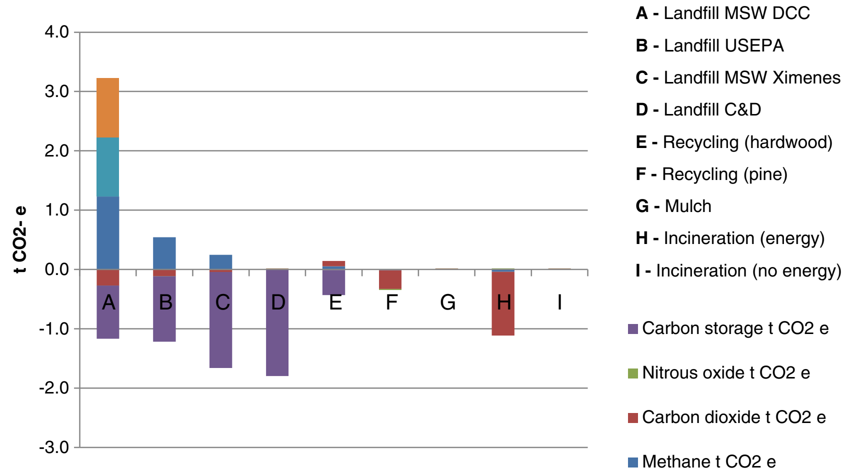
In a recent study (Carre 2011), it was suggested that recycling and disposal in landfill resulted in similar GHG outcomes. It is not clear why such a result was obtained in that

Table 8 Net C storage in wood in landfills as a proportion of total emissions per house component and as an absolute value (timber maximised design)

House component	Affinity (%)	LTCS[a] (tCO_2-e)	Villina (%)	LTCS[a] (tCO_2-e)
Sub-floor	21.1	4.5	22.3	3.4
Walls	21.7	3.1	20.9	4.1
Roof	45.8	4.2	60.8	5.2
Windows	84.4	0.3	84.4	0.4
Floor covering	90.5	2.3	88.4	2.9
Total	–	14.4	–	16

[a] Long-term C storage

Fig. 15 One tonne of timber under different end of life assumptions



study, given that the landfill parameters used were very similar to those applied here, and the recycling impacts were to some extent derived from data from a similar database. In this study, from a greenhouse perspective alone, recycling of wood as a single process resulted in significantly less benefits than the alternatives (see Table 9). However, this does not take into account the fate of the wood once it has been recycled. If the product is eventually disposed of in landfills or incinerated with energy recovery, the GHG savings will be greater than if the products are not recycled at all before being disposed of in landfills or incinerated for energy production.

It is also important to consider the cost–benefit of each option considered. El Hanandeh and El-Zein (2009) estimated the costs of several waste disposal technologies per tonne of waste in NSW. The costs for traditional landfilling were similar to those activities associated with recycling (AUS$ 110–130). The costs for incineration with energy recovery were estimated as approximately double those associated with traditional landfilling and recycling, although the lack of an established waste incineration and energy recovery industry in Australia makes those figures less reliable.

Although the focus of this paper was on global warming as an impact category, the different disposal options may lead to a range of other relevant impacts. Incineration processes for example release emissions into the air and also generate chemical residues. Dijkgraaf and Vollebergh (2004) suggest that the gross environmental costs associated with incineration are significantly higher than those associated with landfilling in the Netherlands—however, inclusion of environmental cost savings due to energy recovery and materials recycling makes the net environmental costs of incineration somewhat lower than those from landfills. For landfills, if leachate is not treated properly it may lead to contamination of groundwater resources. Determination of the toxicity-related impact categories is less certain because suitable methodologies are still under development (Manfredi and Christensen 2009). For a conventional landfill with energy recovery, landfill gas emissions and leachate represent the main contributors to environmental impacts (Manfredi and Christensen 2009). Although for global warming the timeframe of impact assessment is usually 100 years, it is acknowledged that some potential environmental impacts from landfilling such as ecotoxicity and human toxicity may only be realised much later than 100 years (Hauschild et al. 2008), and thus studies of such factors would need to consider longer time frames.

Table 9 Net greenhouse savings of a range of end of life options (average of the timber maximised designs, t $CO2-_e$)

	Landfill US EPA	Recycling[a]	Incineration with energy recovery	Landfill Ximenes	Landfill C&D
Sub-floor (suspended timber)	4.0	1.9	6.5	8.3	10.7
Walls (timber frame brick veneer)	3.6	1.7	5.9	7.6	9.7
Roof (tiled, timber frame)	4.7	2.2	7.7	9.9	12.7
Windows (timber)	0.4	0.2	0.6	0.7	0.9
Floor covering (timber and tiles)	2.6	1.2	4.3	5.5	7.0
Total	15.2	7.2	24.9	31.9	41.0

[a]Mean values for hardwood and softwood

4 Conclusions and recommendations

The study showed that significant GHG emission savings were achieved by maximising the use of wood products for two common house designs in Sydney.

The switch of the sub-floor and floor covering components to a "wood" option accounted for most of the GHG savings.

More specifically the study showed that:

- Although the emissions associated with the extraction, manufacture, transport, use and disposal of materials were significantly lower than operational energy emissions, the choice of materials can significantly impact the overall greenhouse footprint of the house.
- Increased use of timber resulted in significant reductions in GHG emissions for the house designs assessed—however, the potential effect of choice of materials on the operational energy of the houses was not assessed.
- Assumptions of end of life parameters significantly impacted on the outcome of the LCA study.
- Assumptions about extent of decomposition in landfills made a very significant difference to GHG outcomes.
- The most beneficial options for disposal from a greenhouse perspective were landfill (C&D and MSW with low decomposition factor) and incineration with energy recovery.
- If there was an increase in the demand for wood products, the benefits arising from C storage in landfill from timber disposal at the end of life are dependent on whether sustainable levels of timber production are maintained. An increased demand may be met by increases in productivity in existing forests, greater access to existing forests (by increasing the area of natural forests available for harvest) or from increases in the area of plantation managed for sawlogs.
- Although global warming is a very important environmental issue, ideally, important additional indicators such as biodiversity, water emissions and human toxicity (landfilling) should be taken into account.

Finally, a useful follow-up study would assess the thermal performance of building designs, to test how the different materials affect the heating and cooling performance in a range of climatic zones.

Acknowledgments The NSW Department of Environment and Climate Change provided the financial support required to undertake this study. The authors would like to thank Masterton Homes (Mr. Garry Mercer and Mr. Leigh Thompson), for their willingness to participate in the project and patience in providing all the required data. We thank Paul Brooks (NSW DPI) for his assistance with the data collection. Robert Porter (Bradnams), Noel Keating (Canterbury Windows and Doors), Patricia Summer (Bunnings Warehouse) and Wayne Breenan (SteelinHome) provided valuable additional information. The authors are grateful to Mirella Blasi for her assistance with the paper editing, and to Professor Annette Cowie (University of New England) and Mr. Stephen Mitchell (NSW Timber Development Association) for their very helpful comments and suggestions.

References

BIS Shrapnel (2008) Sawn timber in Australia 2008–2022. BIS Shrapnel Forestry Group, June 2008

Buchanan AH, Levine SB (1999) Wood-based building materials and atmospheric carbon emissions. Environ Sci Pol 2:427–437

Carre A (2011) A comparative life cycle assessment of alternative constructions of a typical Australian house design. Report prepared for Forests and Wood Products Australia, PNA147-0809. March 2011

Carre A, Jones I, Bontinck P, Di-Mauro Hayes, G (2009) Extended environmental benefits of recycling (EEBR) Project, Final report. Department of Environment and Climate Change (DECC), Sustainability Programs Division, New South Wales

Cement Industry Federation (2005) Annual report on the Cement Industry Federation ("CIF") Greenhouse Energy Management System ("GEMS") Program—Year Ended 30 June 2004, Manuka

CIE (2007) Capitalising on the building sector's potential to lessen the costs of a broad based GHG emissions cut. Report prepared for ASBEC Climate Change Task Group. Center for International Economics, September 2007

CSIRO (2011) http://www.csiro.au/Organisation-Structure/Flagships/Energy-Transformed-Flagship/AccuRate.aspx

Department of Climate Change (2008) National Greenhouse Accounts (NGA) Factors. Commonwealth of Australia

Department of Climate Change and Energy Efficiency (DCCEE) (2010) Review of the NGER (Measurement) Determination. Discussion Paper, Commonwealth of Australia, August 2010

Department of Climate Change and Energy Efficiency (DCCEE) (2011). Australian National Greenhouse Accounts. National Inventory Report 2009. Vol. 3. The Australian Government Submission to the UN Framework Convention on Climate Change April 2011

Department of Sustainability, Environment, Water, Population and Communities (2008) National Pollutant Inventory. Emission estimation technique manual for combustion in boilers. Version 3.1. Commonwealth of Australia

Dijkgraaf E, Vollebergh HRJ (2004) Burn or bury? A social cost comparison of final waste disposal methods. Ecol Econ 50:233–247

Dimova C (1998a) Life cycle inventory data production of Portland cement and concrete (Readymix) in Australia—Draft Report. CRC for Waste Management and Pollution Control and Centre for Design at. RMIT, Kensington

Dimova C (1998b) Life cycle inventory data production of steel tinplate in Australia. CRC for Waste Management and Pollution Control and Centre for Design at RMIT, Kensington

ecoinvent Centre (2007) ecoinvent data version 2.0, Overview and Methodology. ecoinvent Report No. 1. Dübendorf, Swiss Centre for Life Cycle Inventories

El Hanandeh A, El-Zein A (2009) Strategies for the municipal waste management system to take advantage of carbon trading under competing policies: the role of energy from waste in Sydney. Waste Manage 29:2188–2194

Gustavsson L, Joelsson A (2010) Life cycle primary energy analysis of residential buildings. Energ Buildings 42:210–220

Gustavsson L, Pingoud K, Sathre R (2006) Carbon dioxide balance of wood substitution: comparing concrete and woodframed buildings. Mitig Adapt Strateg Glob Chang 11(3):667–691

Hauschild M, Olsen SI, Hansen E, Schmidt A (2008) Gone…but not away—addressing the problem of long-term impacts from landfills in LCA. Int J Life Cycle Assess 13:547–554

HIA (Housing Industry Association) (2008) Housing 100 2006/07—Australia's largest home builders and residential developers. HIA Economics group, ACT

Hyder Consulting (2010) Comparative Greenhouse Gas Life Cycle Assessment of Wollert Landfill. Report prepared for Hanson Landfill Services and the City of Whittlesea. Melbourne, VIC, Australia

Lippke B, Oneil E, Harrison R, Skog K, Gustavsson L, Sathre R (2011) Life cycle impacts of forest management and wood utilisation on carbon mitigation; knowns and unknowns. Carbon Mitig 2 (3):303–333

Manfredi S, Christensen TH (2009) Environmental assessment of solid waste landfilling technologies by means of LCA-modeling. Waste Man 29:32–43

May B, England JR, Raison JR, Paul KI (2011) Cradle-to-gate inventory of wood production from Australian softwood plantations and native hardwood forests: embodied energy, water use and other inputs. Forest Ecol Manage 264:37–50

McLennan Magasanik Associates (1991) Energy usage in timber framing. Report to the National Association of Forest Industries, Australia

McLennan Magasanik Associates (2010) Climate change and the resource recovery and waste Sectors. A report prepared for the Department of the Environment, Water, Heritage and the Arts, April 2010

Penman T, Law B, Ximenes F (2010) A proposal for accounting for biodiversity in life cycle assessment. Biodiver Conserv 19:3245–3254

Perez-Garcia J, Lippke B, Briggs D, Wilson JB, Boyer J, Meil J (2005) The environmental performance of renewable building materials in the context of residential construction. Wood Fiber Sci 37:3–17

Petersen AK, Solberg B (2004) GHG emissions and costs over the life cycle of wood and alternative flooring materials. Clim Chang 64:143–167

ROU (2006) Life cycle inventory and life cycle assessment for windrow composting systems. Recycled Organics Unit, University of New South Wales. Report prepared for the Department of Environment and Conservation NSW

Salazar J, Meil J (2009) Prospects for carbon-neutral housing: the influence of greater wood use on the carbon footprint of a single-family residence. J Clean Prod 17(17):1563–1571

Sathre RJ, O'Connor J (2010) Meta-analysis of greenhouse gas displacement factors of wood product substitution. Environ Sci Pol 13:104–114

Strezov L, Herbertson J (2006) A life cycle perspective on steel building materials. Australian Steel Institute, Newcastle

Tucker S, Tharumarajah A, May B, England J, Paul K, Hall M, Mitchell P, Rouwette R, Seo S, Syme M (2009) Life cycle inventory of Australian forests and wood products. FWPA Report, Project No. PNA008-0708

UNEP (2007) Buildings and climate change: status, challenges and opportunities. United Nations Environment Program, http://www.unep.fr/shared/publications/pdf/DTIx0916xPA-BuildingsClimate.pdf

Upton B, Miner R, Spinney M (2006) Energy and GHG impacts of substituting wood products for non-wood alternatives in residential construction in the United States. National Council for Air and Stream Improvement, Technical Bulletin No. 925, November 2006

US EPA (2006) Solid waste management and greenhouse gases. A life cycle assessment of emissions and sinks, 3rd Edition, September 2006

US EPA (2011) Reducing GHG emissions through recycling and composting. EPA 910-R-11-003. May 2011 http://www.epa.gov/region10/pdf/climate/wccmmf/Reducing_GHGs_through_Recycling_and_Composting.pdf

Ximenes FA, Gardner WD (2005) Production and use of forest products in Australia. Forest Resources Research—NSW Department of Primary Industries Technical Paper No. 71

Ximenes FA, Gardner WD, Cowie A (2008a) The decomposition of wood products in landfills in Sydney, Australia. Waste Manage 28 (11):2344–2354

Ximenes FA, Kapambwe M, Keenan R (2008b) Timber use in residential construction and demolition. BEDP Environ Design Guide, November, PRO36

Wang X, Padgett JM, De la Cruz FB, Barlaz MA (2011) Wood biodegradation in laboratory-scale landfills. Environ Sci Technol 45(16):6864–6871